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Tribo-functional effects of double-crossed helix on surface finish, cutting friction and tool wear mechanisms during the milling process of natural fiber composites

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Tribological mechanisms that control the machining of natural fiber reinforced plastic (NFRP) composites are different from those of synthetic fiber composites in terms of cutting forces, tool wear, and surface finish. The aim of this paper is to investigate the cutting performances of NFRP composites using improved milling tool geometry with double-crossed helix (DCH). Cutting edges are coated with PVD-TiAlN thin coating thickness to ensure low cutting edge radius. Milling experiments are performed on unidirectional flax fibers reinforced polypropylene composites with CNC machine varying the tool kinematics. The in-situ cutting forces are acquired to evaluate the tribological performances of machining NFRP with DCH tool. The machined surfaces are rated by Scanning Electron Microscope (SEM) and peripheral surface defects are rated using an optical microscope. Moreover, the tool wear is evaluated at the cutting tool edge by SEM observations after accelerated wear tests. Results show that the improved milling tool overcomes the disadvantages and limitations of known NFRP machining in terms of surface finish. The functional design of the DCH generates a specific tool wear behavior where the wear mechanisms differ at each cutting helix orientation.

1. Introduction

Natural fiber reinforced plastic (NFRP) composites are new bio-composite products that attract the industrial world. In fact, the use of natural fibers, especially plant fibers, as reinforcement for composite materials has become increasingly common in many industrial sectors as a substitute for synthetic glass fibers [1,2]. NFRP composites are manufactured with plant fibers and a polymer matrix to produce industrial composite parts with short fibers reinforcement [3], long fibers reinforcement [4], or sandwich-structured composites [5]. This strong demand is justified by the technical, economic, and ecological performances offered by plant fibers in different industrial applications to reduce environmental impacts and thus contribute to the development of a circular and sustainable economy [6,7]. Thanks to all these advantages, NFRP composites are nowadays used for many industrial applications, especially for the automotive industry to produce interior and exterior structural panels for vehicles [8–12].

The strong demand for bio-composite materials requires deep investigations into their manufacturing processes to optimize their production [13], especially during machining operation where the cutting

behavior of natural fibers presents some issues due to their complex cellulosic structure [14] that makes them highly sensitive to the variation of process parameters. Because of this cellulosic structure, mechanical properties of NFRP composites have a multiscale dependence on the analysis contact scale [15,16]. A particular problem in the milling of NFRP is that of holding good surface finish, which is significantly dependent on the fiber type [17] and the tool geometry such as the cutting edge sharpness [18] and the helix angle of the cutting flutes [19]. Indeed, increasing slightly the cutting edge radius increases strongly the cutting energy. This behavior has been related to the micro-area of the cutting contact that increases by increasing the cutting edge radius. Consequently, a transverse deformation of fibers is first occurred before fibers shearing due to the lowering of the cutting contact stiffness [18]. On the other hand, increasing the tool helix angle decreases significantly the cutting friction but increases the machining damages in terms of fibers fluffing at the surface periphery, especially at the exit of the cutting edge flute where the fibers maintaining is poor [19]. A zero helix angle is then appropriate to produce a good surface finish. However, the fact that reducing the tool helix angle increases the cutting friction could have a significant impact on the cutting tool by

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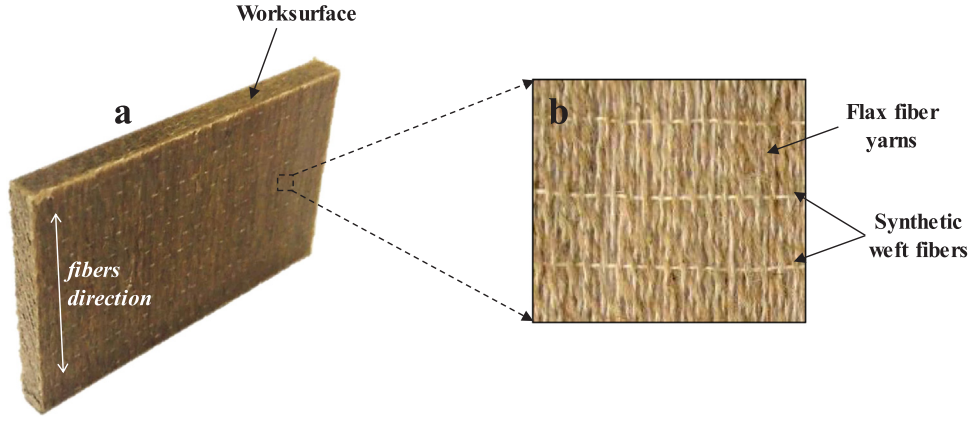


Fig. 1. (a) Photograph of UDF/PP workpiece. (b) Image of flax fibers reinforcement structure.

Table 1

Mechanical properties of NFRP workpieces and their components.

	Flax fiber	PP matrix	UDF/PP
Tensile modulus (GPa)	50	0.93	17.6
Tensile strength (MPa)	500	29.5	109
Maximum strain	2%	14%	1.3%

accelerating the tool wear.

For synthetic fiber (glass and carbon) composites, it has been demonstrated that the machining tool wear is controlled by the abrasion mechanism on the flank tool face which is due to the abrasive character of glass and carbon fibers [20–23]. Concretely, since the chip is generally discontinuous in the case of synthetic fiber composites, the tool wear on the rake face is usually reduced and not predominant. Nevertheless, the high spring-back of glass and carbon fibers on the newly machined surface causes a severe frictional contact between the flank tool face and the abrasive fibers [24]. Moreover, the fiber debris entrapped between the machined surface and the flank face give rise to three-body abrasion conditions [24]. In the case of NFRP composites, natural fibers are well known as less abrasive to processing equipment [25,26] and, therefore, the tool wear mechanisms may be different from those of synthetic fiber composites. Unfortunately, literature works have not yet addressed the issue of tool wear in the case of machining NFRP composites.

For all the above reasons, one solution to reduce the machined surfaces damages without reducing the tool helix angle is to orientate the cutting edge flutes toward each surface borders. This could reduce the fluffing damages at the surface peripheries without increasing severely the frictional forces. In this paper, this solution is investigated with a double-crossed helix (DCH) milling tool to ensure two opposing

Table 2

Cutting configurations for the milling experiments.

Config. no.	Depth of cut a_p (mm)	Cutting speed V_c (m/min)	Feed f_z (mm/tooth)
1	1	100	0.04
2	1	100	0.06
3	1	100	0.08
4	1	100	0.1
5	1	200	0.04
6	1	200	0.06
7	1	200	0.08
8	1	200	0.1
9	1	300	0.04
10	1	300	0.06
11	1	300	0.08
12	1	300	0.1

orientations of the cutting edge flute. The DCH tool is used for machining unidirectional flax fibers reinforced polypropylene composites. The aim of this study is to investigate the cutting performances of DCH milling tool in terms of surface finish, surface damages, and tool wear.

2. Experimental procedure

NFRP composites used in this paper (Fig. 1(a)) are composed of 40% of unidirectional flax fibers that are twisted into yarns and 60% of polypropylene matrix (UDF/PP). Synthetic weft yarns (Fig. 1(b)) are introduced to ensure the unidirectionality of flax fibers during the thermo-compression molding process and they take about 5% of the total fabric. Each sample used in machining tests has the following dimensions ($45 \times 25 \times 4$ mm). All the NFRP workpieces are manufactured and supplied by “Composites Evolution – UK”. The main

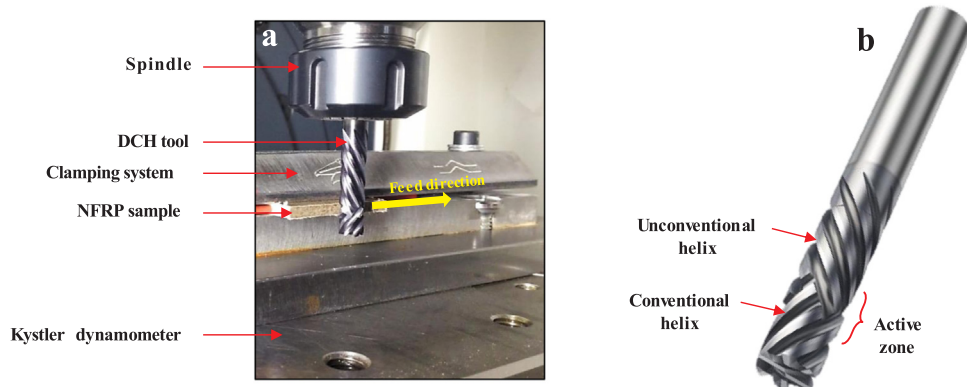


Fig. 2. (a) Image of the experimental setup for milling tests. (b) Photograph of the DCH tool.

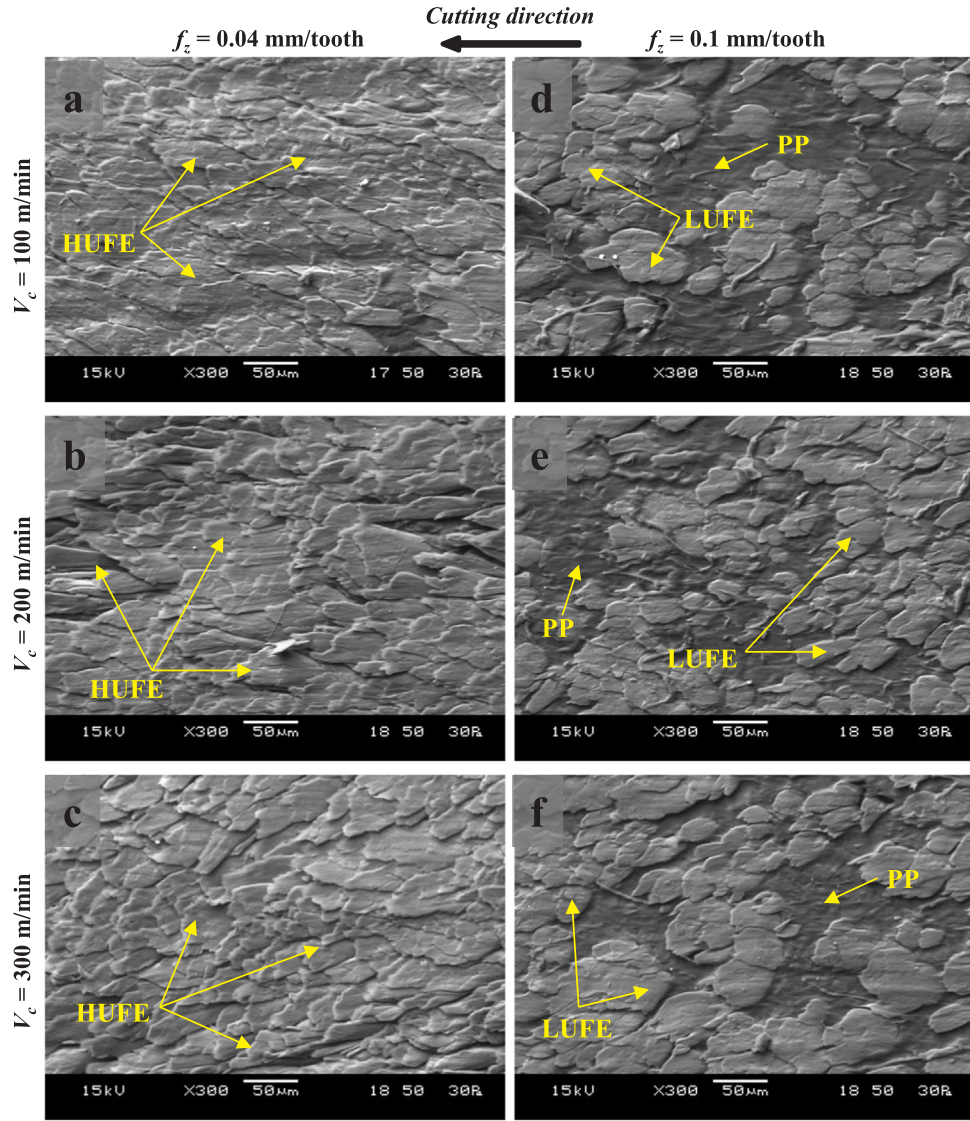


Fig. 3. SEM images of the machined surface state of UDF/PP composites at different cutting conditions. “HUFE”: High Uncut Fiber Extremities; “LUFE”: Low Uncut Fiber Extremities; “PP”: Polypropylene matrix.

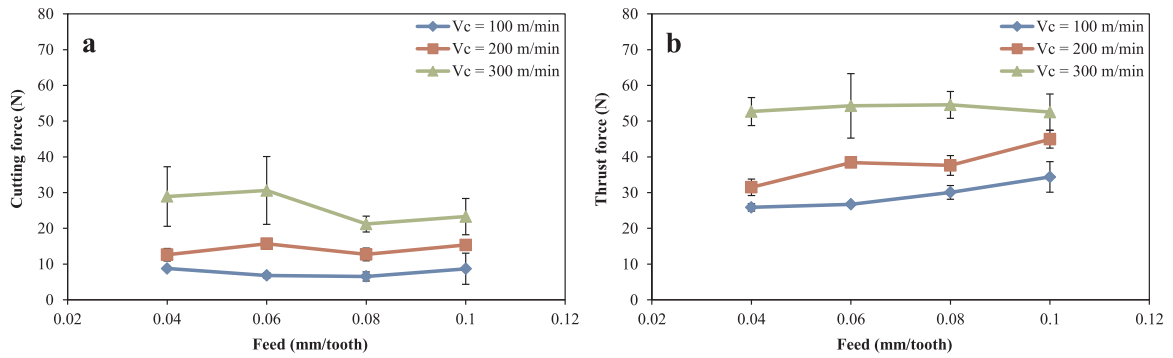


Fig. 4. Machining forces graphs of UDF/PP composite with DCH tool. (a) Cutting forces and (b) Thrust forces.

mechanical properties of each composite component are given in Table 1 as provided by the supplier. All the NFRP worksurfaces are initially polished with the same grit size and the same polishing procedure to ensure an identical initial state before machining experiments.

Milling experiments are performed on DMG-MORI five axes CNC machine (Ref. CMX U50) that is equipped with a Kistler dynamometer

(Ref. 9255B) to acquire the in-situ cutting forces as shown in Fig. 2(a). The flax fibers orientation is perpendicular to the feed direction. The DCH tool is provided by “Sandvik Coromant – FR” (Ref. 2P460-0952-NA1630) and is illustrated in Fig. 2(b). It is composed of six cutting edges. Each edge has two helical flute orientations. Both have an absolute helix angle value of 30°. However, the bottom helical flute is oriented toward the conventional direction (+ 30°) and the top helical

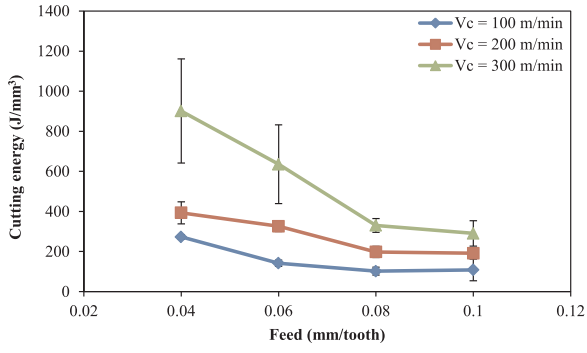


Fig. 5. Specific cutting energy when milling UDF/PP composite with DCH tool.

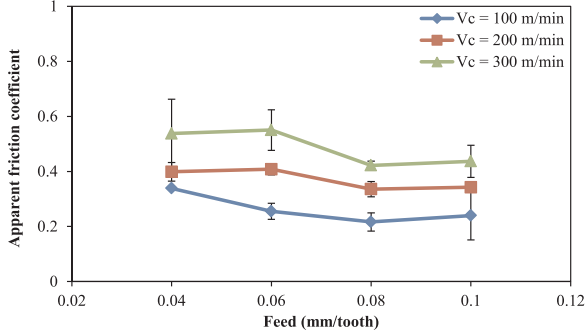


Fig. 6. Apparent cutting friction coefficient between DCH tool and UDF/PP composite during milling.

flute is oriented toward the opposite (unconventional) direction (-30°). The active zone of the milling tool where the cutting has occurred is centered in the limit between the two helical flute orientations as shown in Fig. 2(b). Cutting edges of the DCH tool are coated with PVD-TiAlN thin coating thickness ($\sim 1.5 \mu\text{m}$) to avoid microcracks at the tip of the cutting edge when machining without increasing significantly the cutting edge radius.

Cutting tests are performed by varying the tool kinematics (cutting speed and feed) as summarized in Table 2. Each cutting configuration of Table 2 is repeated at least three times to ensure the repeatability. The output values from milling experiments are presented as the mean of these three repeated tests. Errors are considered as the average of the absolute deviations of data repeatability tests from their mean.

For post machining analysis, scanning electron microscope (SEM) (JSM — 5510LV) is used to evaluate the microscopic state of machined surfaces and also to characterize the wear behavior of the milling tool. Moreover, an optical microscope (Nikon SMZ 745T) is used to rate the surface damages at the surface borders.

3. Results and discussion

3.1. Microscopic cutting behavior of flax fibers

Fig. 3 shows typical SEM images that illustrate the microscopic surface state of flax fiber composites after machining. The cutting behavior of flax fibers is different when changing the cutting conditions. The cutting feed has the most important influence where increasing the feed from 0.04 mm/tooth to 0.1 mm/tooth improves considerably the fibers shearing. This can be observed in Fig. 3 at all the considered range of cutting speed where the uncut fiber extremities decrease significantly by increasing the feed. Moreover, the effect of the cutting speed is more obvious at low feed values where increasing the cutting speed deteriorates the flax fibers shearing as shown between Fig. 3(a)–(c). The rate of uncut fiber extremities is so high at low feed that the PP matrix is no longer obvious on the SEM images. However, when increasing the feed, the effect of the cutting speed becomes insignificant.

The cutting feed has an important effect on the cutting behavior of flax fibers as it controls the removed chip thickness. Increasing the cutting feed increases the removed chip thickness until reaching the minimum chip thickness required for a good material shearing. On the other side, the fact that the cutting speed affects the cutting behavior at low feed values may be due to a thermal effect that can be induced by increasing the cutting speed as reported also for synthetic fiber

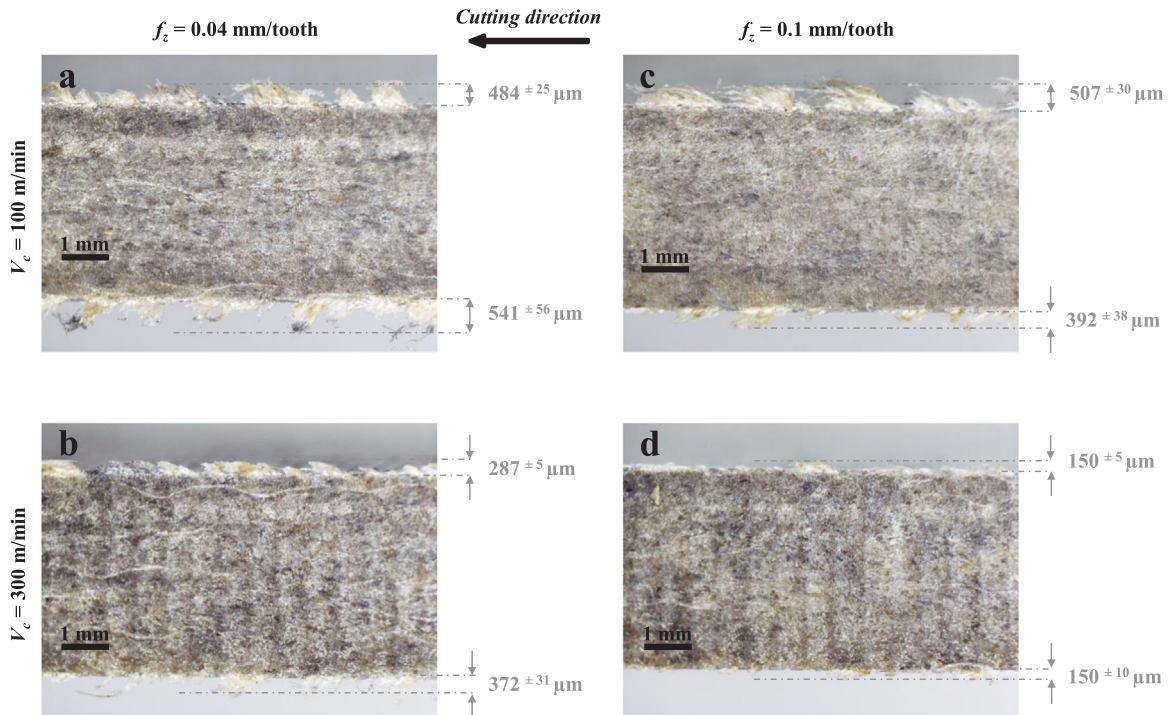


Fig. 7. Optical microscope images of UDF/PP machined surfaces showing the fluffing defects.

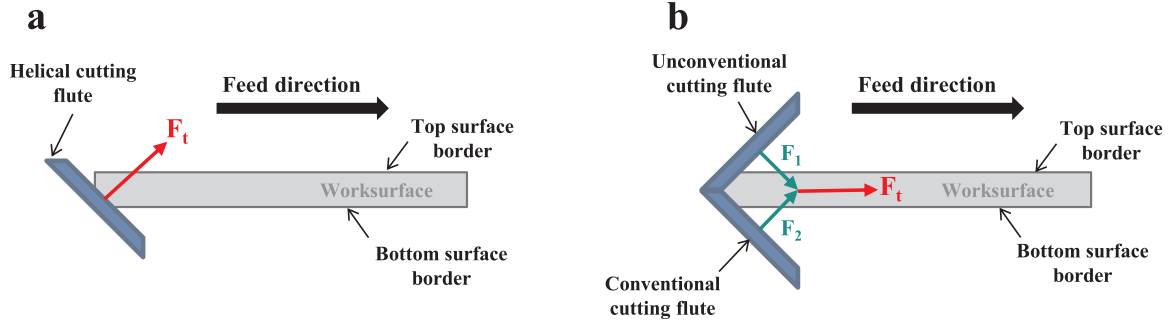


Fig. 8. Schematic depiction of the cutting configuration using (a) conventional milling tool, and (b) DCH milling tool.

composites in [27,28]. Increasing the cutting speed increases the temperature at the cutting contact interface, especially when cutting with low feed because the cutting contact lasts longer. This induces a high temperature at the worksurface which makes the fibers and the matrix softer. Therefore, flax fibers lose their stiffness and also the PP matrix support due to the thermal softening of the polymer as reported in [29].

3.2. Tribo-performances of DCH tool on UDF/PP composites

The tribo-functional analysis of DCH tool is performed in this section using the measured machining forces. The Kystler dynamometer acquires the machining forces in the Cartesian coordinate system (X,Y,Z). The machining forces in the case of milling followed the cylindrical coordinate system of the milling tool. Therefore, cutting forces (tangential force in the cylindrical coordinate system) and thrust forces (radial forces in the cylindrical coordinate system) are calculated as described in [30]. Thus, the specific cutting energy and the apparent cutting friction coefficient can be deduced as shown and described in [17,19]. The specific cutting (E_{sc} (J/mm³)) energy is calculated following Eq. (1) where P (W) is the cutting power and Q (mm³/min) is the chip rate. The cutting power can be calculated from the cutting force (F_c (N)) and the cutting speed following Eq. (2), while the chip rate is deduced from the depth of cut (a_p (mm)), the sample thickness (e (mm)) and the feed speed (V_f (mm/min)) using Eq. (3). The apparent cutting friction coefficient (μ_{app}) is calculated as the ratio between the cutting force (F_c (N)) and the thrust force (F_{th} (N)) following Eq. (4).

$$E_{sc} = \frac{P}{Q} \quad (1)$$

$$P = F_c \times V_c \quad (2)$$

$$Q = a_p \times e \times V_f \quad (3)$$

$$\mu_{app} = \frac{F_c}{F_{th}} \quad (4)$$

Fig. 4 presents both cutting forces and thrust forces during the milling experiments. Thrust forces are higher than cutting forces in the case of DCH tool. Increasing the cutting speed increases both the cutting force and the thrust force for all the cutting configurations. A similar behavior regarding the effect of the cutting speed has been reported for the drilling of natural fibers composites in [31]. However, the effect of cutting feed is not significantly obvious. Considering the standard deviation of the measurements, there is a slight decreasing with feed of the cutting force at $V_c = 300$ m/min (Fig. 4(a)) and a slight increasing with feed of the thrust force when cutting with $V_c = 100$ m/min and $V_c = 200$ m/min (Fig. 4(b)). The cutting feed is the major parameter that influences the cutting behavior of flax fibers when machining as shown in Fig. 3 but its effect is not visible on the machining forces of Fig. 4. Therefore, the machining forces do not describe efficiently the cutting behavior of flax fibers in the composite which is different from the cutting behavior of synthetic fiber composites [32].

Using the concept of specific cutting energy, which is the energy

necessary to remove an elementary volume of material, Fig. 5 shows that the highest cutting speed (300 m/min) generates the highest energy. The effect of the cutting speed is more visible at low cutting feed. When increasing the feed, the effect of the cutting speed becomes insignificant. Moreover, increasing the cutting feed decreases the energy dissipated by machining, especially at high cutting speed. This energetic analysis corresponds to the cutting behavior of flax fibers shown in Fig. 3. The specific cutting energy of Fig. 5 reflects thus the shearing efficiency of flax fibers in the composite where the decrease of the energy values means an efficient fiber shearing during cutting operations. The easiest flax fibers are sheared, the lowest cutting energy is generated.

To better understand the tribo-performances of the DCH tool, the apparent friction coefficient, which is defined locally by the ratio between the cutting force and the thrust force of Fig. 4, is calculated and presented in Fig. 6. The cutting friction behavior between UDF/PP composites and the DCH tool shows an important dependence on the cutting speed. Increasing the cutting speed increases the cutting contact friction. On the other side, increasing the cutting feed decreases slightly the friction coefficient. The friction rising with cutting speed may be due to the thermal generation (explained in Section 3.1) that activates an adhesive friction between the tool face and the polymeric contents of the NFRP composite due to their thermal softening. Increasing the cutting feed decreases this thermal generation by reducing the cutting contact time. These tribo-thermal phenomena occurred at the cutting contact interface could impact the tool wear. The wear issues will be investigated in the last section of this paper.

3.3. Improved machining defects with DCH tool

Machining of natural fiber composites induces important damages at the surface peripheries that so-called “fluffing defects” [18,19]. Fig. 7 shows the fluffing defects in terms of fluffing length at the machined surface borders. Fluffing defect is affected by the tool kinematics. The maximum of fluffing length is detected at low cutting speed and low feed (Fig. 7(a)). The cutting speed has the largest effect on fluffing defects where increasing the cutting speed from 100 m/min to 300 m/min decreases significantly the fluffing length. The effect of the cutting feed is more visible at high cutting speed (from Fig. 7(b) to Fig. 7(d)) where increasing the feed also reduces the fluffing defects.

The maximum fluffing length obtained in this study is 541 ± 56 μ m which is largely lower than that obtained at similar process parameters but with a conventional milling tool that has one cutting helix flute orientation [18]. These damages concern flax fibers that are near to the borders of the machined surface of the composite because these zones suffer for poor fibers maintaining, especially at the exit of the cutting helix flute since the cutting force is oriented outward the workpiece as shown in Fig. 8(a). Indeed, machining with conventional milling tool reduces the fluffing defects at the entry of the cutting flute (the bottom surface border in Fig. 8(a)) but increases the fluffing defects at the exit of the cutting flute (the top surface border in Fig. 8(a)) [18].

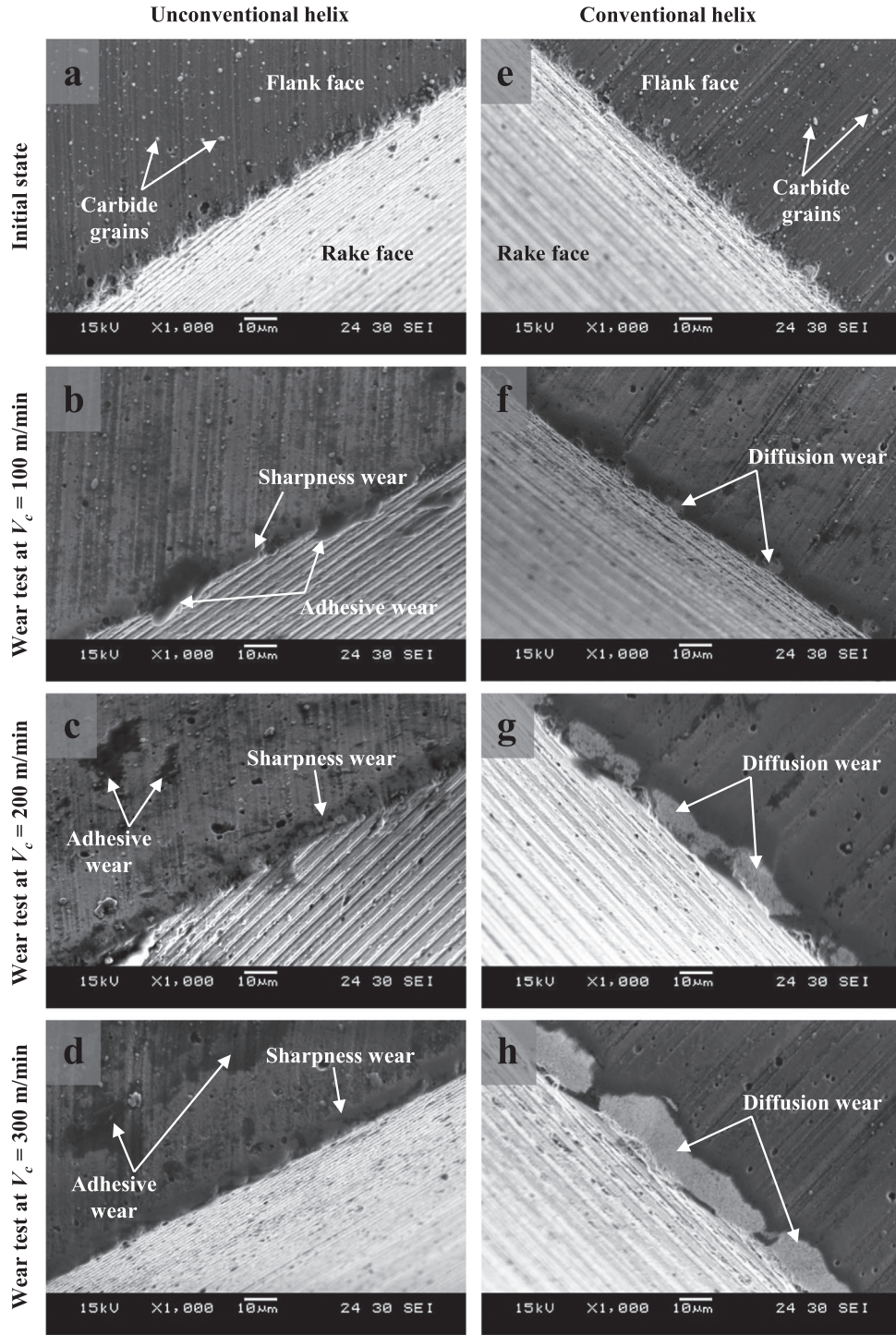


Fig. 9. SEM images of the active cutting edges of the DCH tool before and after each wear test.

In the case of DCH tool, both top and bottom surface borders have a better maintaining during cutting operation because the double-crossed helix flutes make the cutting edge oriented toward each surface border as shown in Fig. 8(b). Therefore, at each surface border, cutting forces are oriented inside the worksurface which provides a strong fiber maintaining on the two sides of the worksurface thanks to the internal composite material.

3.4. Wear analysis of DCH milling tool

To investigate the wear behavior of the DCH milling tool,

accelerated wear test is performed after cutting experiments. A UDF/PP workpiece with the dimensions of $(140 \times 30 \times 4 \text{ mm})$ is used for the wear tests. The accelerated wear test consists of successive cutting passes all over the cutting length of 140 mm with a small cutting depth and a low feed rate. Therefore, a cutting depth of 0.1 mm is considered with a feed rate of 80 mm/min. Since the workpiece width is 30 mm, a clamping width of 10 mm allows a total depth of cut of 20 mm which generates 200 cutting passes. Each wear test takes then 350 min. The three cutting speed values considered in this study (100, 200 and 300 m/min) are explored for the wear analysis.

Fig. 9 shows the wear behavior at the flank faces of both the

conventional (CNV) and the unconventional (UCNV) cutting helix flutes. At the initial state, CNV and UCNV flank faces have the same microscopic morphology (Fig. 9(a) and Fig. 9(e)). Carbide grains are observed on the flank faces of CNV and UCNV edges because the TiAlN coating is very thin (1.5 μm) and cannot cover the solid carbide morphology. Moreover, the cutting edge tip is not round at the initial state. As seen in Fig. 9(a) and Fig. 9(e), the junction between the flank face and the rake face is not smooth and not continuous since the cutting edges have several micro-cracks of carbide material all over the edge tip. This issue is due to the manufacturing process of the DCH tool in order to make the cutting edges as sharp as possible. After the wear test, carbide grains are reduced from the flank of the UCNV cutting edge (Fig. 9(b)–(d)). However, carbide grains are removed from the flank face of the CNV cutting edge when performing the wear test with a cutting speed of 300 m/min (Fig. 9(h)). This proves that the two cutting edges did not undergo the same tribo-mechanical solicitations.

Microscopic observations of Fig. 9 show that the wear behaviors of CNV and UCNV edges are not similar. At the CNV cutting edge, a TiAlN coating removal from the flank face is observed near to the tip of the cutting edge. The TiAlN coating removal increases significantly when increasing the cutting speed from 100 m/min to 300 m/min (Fig. 9(f) \rightarrow Fig. 9(g) \rightarrow Fig. 9(h)). Unlike glass or carbon fibers, no sign of abrasion is detected. This is logic because natural fibers are not abrasive. The TiAlN coating removal from the flank face may be due to a diffusion wear caused by the induced friction temperature. This thermal effect, which increases by cutting speed increase, leads to atoms release from the TiAlN thin coating film with the high tribo-mechanical cutting solicitations.

However, UCNV cutting edge does not show the same wear mechanisms. Fig. 9(b)–(d) indicate that the main wear on the UCNV cutting edge is on the edge tip where this latter becomes smoother and more rounded between the flank face and the rake face which increases the cutting edge radius and, consequently, reduces the cutting edge sharpness. This is what it called “sharpness wear” in Fig. 9 and this wear type is significantly important in the case of machining NFRP composites [18]. Sharpness wear is not significantly affected by changing the cutting speed. Moreover, adhesive wear is also detected on the UCNV cutting edge and it is more obvious with high cutting speed because of the thermal effect discussed previously.

This investigation demonstrates that the induced temperature due to cutting frictions and high plastic deformation rates especially controls the tool wear in the case of NFRP machining. This thermal effect is more important when machining NFRP composites because both natural fibers and polymer matrix are not thermally conductive and, therefore, the induced cutting temperature remains on the cutting interface.

4. Conclusions

This paper investigates improved milling tool geometry for machining natural fiber reinforced plastic (NFRP) composites. This milling tool is characterized by a double-crossed helix (DCH) and is tested with unidirectional flax fibers reinforced polypropylene (UDF/PP) composites. Both cutting performances and tool wear are explored in this study. The following conclusions can be drawn:

- From the microscopic observations, the cutting feed has the most significant impact on the flax fibers shearing where increasing the feed improves the shearing efficiency. However, increasing the cutting speed reduces the shearing efficiency of flax fibers. The same observations are retained from the energetic analysis where increasing the feed from 0.04 mm/tooth to 0.1 mm/tooth decreases the specific cutting energy by 67% for a cutting speed of 300 m/min, 51% for a cutting speed of 200 m/min and 60% for a cutting speed of 100 m/min.
- The cutting speed influences the cutting friction. Increasing the

cutting speed from 100 m/min to 300 m/min increases the apparent friction coefficient by 60% for a feed of 0.04 mm/tooth, 120% for a feed of 0.06 mm/tooth, 100% for a feed of 0.08 mm/tooth and 87% for a feed of 0.1 mm/tooth.

- Cutting with DCH milling tool improves considerably the surface finish in terms of fluffing defects at the surface borders comparing with standard milling tools.
- Although the increase in cutting speed has a negative effect on the flax fibers shearing, increasing the cutting speed reduces the fluffing defects on the machined surface borders by 30–40% for low feed (0.04 mm/tooth) and 60–70% for high feed (0.1 mm/tooth) which improves the surface finish.
- For milling NFRP composites with DCH tool, the wear mechanisms are not the same on the conventional and the unconventional cutting edges. Diffusion wear is the main wear mechanism in the conventional edge while sharpness wear remains the important wear mechanism in the unconventional cutting edge. Further tribo-mechanical investigations will be performed by the authors to understand more the origin of wear difference between the two helix orientations.

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